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A NUMERICAL ANALYSIS OF LOAD SHARING AND IMPLANT POSITIONING ON THE STRESS DISTRIBUTION IN A TIBIAL BONE

B. Innocenti[1], L. Labey[2], P. Wong[3] and J. Bellemans[4]

1. ABSTRACT

The aim of the present work was to estimate the effect of prosthesis positioning and of load sharing on the VonMises stress distribution in a tibial bone. The analysis was focused on three main bone regions: the medial periprosthetic region, the lateral periprosthetic region and the bone-prosthesis interface region. A three-dimensional static finite element analysis of a tibia with a cementless baseplate was performed. The geometric model of the bone was based on a standard tibia model in which a commercial knee prosthesis was implanted. In this study eleven different load conditions and nine prosthesis positions were considered. The FE analysis shows an influence of baseplate positioning, and also of load sharing, on the average VonMises stresses in the considered regions. The average stress in the bone prosthesis interfacial region was not sensitive to implant position, and was moderately sensitive to load sharing. The average stress in the lateral periprosthetic region presented linear relationships with implant positioning and load sharing. The average stress in the medial periprosthetic region presented a similar trend as the lateral region regarding load sharing, but it showed a non linear relationship with implant positioning.

2. INTRODUCTION

Bone is a living material which is able, as opposed to synthetic materials, to adapt to the load conditions to which it is subjected. For example, it has been demonstrated that an insufficient use of the limbs or long exposure to weak gravitational fields induces a reduction of the bony mass. Alternatively, if a bone is subjected to mechanical loading which is higher than physiological, the bone will increase its mass. This phenomenon is called bone remodelling, and it induces geometric and density changes in the bone which are different from normal growth, and which are necessary to maintain the stresses in specific ranges [1-2].
As already asserted by Wolff in 1892, bony morphology is influenced by the applied loads, and every deviation of the usual load conditions produces a change in the bony tissue architecture [3].

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Therefore, any factor that modifies the stress distribution inside the bone can induce a new bony configuration. For instance, the insertion of an implant in a bone produces an alteration of the mechanical environment (i.e. material, shape) that induces a different load condition on the bone compared to the physiological one. Such non physiological distribution of the loads around the prosthesis is one of the main causes of failure of the prosthetic implants because it can cause bone loss and aseptic loosening of the implant in the long term [4-6].

Several parameters, such as design of the implant, its material properties and its fixation technique, can lead to stress alteration in the bone. Finite element analysis (FEA) of a prosthesis-tibia constructs have already been performed in the past to find their effects. Also the load conditions at the tibio-femoral interface and the prosthesis position may affect the stress distribution, but these parameters have not been thoroughly examined [7-9].

To try to find the relationships that both load sharing and implant positioning have with the stress in the periprosthetic bone region, a static FEA of a prosthetized tibial has been performed. The investigation was focused on three main bone regions: the medial periprosthetic region, the lateral periprosthetic region and the bone-prosthesis interface region. Eleven load conditions and nine prosthesis positions were analyzed.

3. MATERIALS AND METHODS

A three-dimensional finite element model of a prosthesis-tibia construct was developed from a public tibia model [10]. The cortical bone was modeled with a constant thickness of 2 mm. This bone model was prepared for receiving the Genesis II (Smith & Nephew, Memphis, TN) asymmetric titanium tibial baseplate and its UHMWPE insert. A size 5 baseplate was chosen for this study since it is a common size used in clinical practice. The bone model was scaled uniformly such that the resected proximal bone surface would be 3.0 mm longer in the mediolateral (ML) direction than the baseplate to allow for an analysis of the ML prosthesis position. The prosthesis was implanted in the tibia according to the surgical technique at an 11 mm tibial resection level perpendicular to the intramedullary canal. The baseplate was placed initially in a “centered” ML position, at 1.5 mm from both the medial and the lateral edge of the bone (Fig. 1). A hole was cut into the bone conforming to the shape of the baseplate stem and fin geometry, with a 1 mm gap left between the bone and the stem (Fig. 2). When the implant was repositioned, the hole was repositioned accordingly.

We defined three regions in the tibial bone, the medial periprosthetic region, the lateral periprosthetic region and the bone-prosthesis interface region. The medial and the lateral regions had heights of 5 mm, widths of 10 mm, and anteroposterior lengths that spanned the bone (Fig. 1).

The tibial model was trimmed distally and the cut section was considered fixed in all the simulations. The components were meshed with approximately 35,000 elements, using modified 8-node tetrahedrals; the mesh density was increased for the three regions considered (Fig. 2).

Friction contact was considered between bone and baseplate and also between baseplate and insert. The values of the coefficient of friction (0.20 for the bone-titanium baseplate interface and 0.15 for the insert-titanium baseplate interface) were chosen according to literature [11].

Similar to several other studies [7, 8, 12, 13] linear elastic material models were used for the cortical and for the cancellous bone. Also the titanium alloy was considered a linear elastic material. The material properties for cancellous bone, cortical bone and titanium alloy are shown in table I.

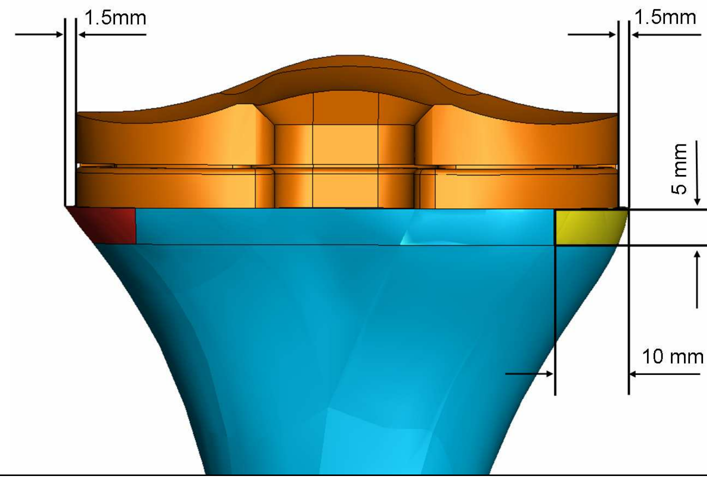

Figure 1: Central position of the prosthesis in the tibia model; the baseplate is equidistant from the medial and lateral edges of the bone. The medial and lateral regions are dimensioned and colored. The picture shows only the proximal bone.

The UHMWPE was assumed to be a non-linear elastic plastic material according to literature [14-15] with the following properties:

- Elastic properties: E = 684.65 MPa, $\upsilon = 0.33$
- Plastic properties:

True stress (MPa)	True Strain
25.704	0.1044
25.545	0.1808
29.227	0.2874

Table I: Material properties and material behavior used in this study

Material	**Young's Modulus E (GPa)**	**Poisson's ratio**	**Material behavior**
Cortical Bone	16.6	0.3	Homogeneous, linearly elastic, isotropic
Cancellous Bone	2.4	0.3	Homogeneous, linearly elastic, isotropic
Titanium Alloy (Ti6Al4V)	117	0.3	Homogeneous, linearly elastic, isotropic

The load was applied on two different contact areas on the polyethylene insert. These areas were defined at 10° flexion according to a previous static experimental contact area study on a size 5 Genesis II femoral component against a size 5-6 tibial insert. Based on those results, ellipsoid contact faces on the medial and lateral condyles were created on the insert with areas of 121 mm^2 and 132 mm^2, respectively in the same position as in the experiment. An 800 N static load, corresponding to average body weight, was shared between the two areas in eleven load distributions, ranging from 0 to 100% (100 to 0%) on the lateral (medial) condyle with steps of 10%. The load on each face was distributed homogeneously and perpendicular to the baseplate. For each load distribution, nine baseplate positions were simulated, ranging from 0.25 mm overhang on the medial condyle to 0.25 mm overhang on the lateral condyle. The baseplate was positioned in 0.5 mm steps away from the centered ML position, up to the edges of the bone and to an additional 0.25 mm past the edges. Ninety-nine simulations were run in total (11 load conditions - 9 positions). For each simulation, the average VonMises stresses in each region was evaluated and plotted versus lateral load share and implant positioning. Abaqus/Implicit Version 6.6- (Abaqus, Inc., Providence, RI, USA) was used to perform all the finite element simulations.

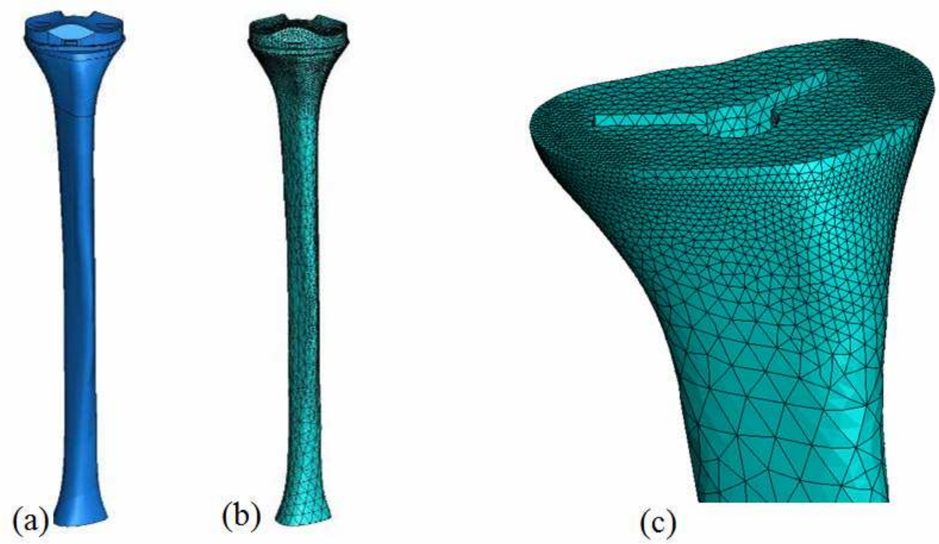

Fig.2: FEM of the prosthesis-tibia construct: a) Geometric model; b) FEM mesh; c) Proximal view showing a higher density of the mesh in the three regions.

4. RESULTS

4.1 Bone-prosthesis interface region

The results of the FEA showed that stress in the interfacial region was lowest when load sharing was equal between the medial and lateral regions. (Fig. 3a). The average stress in the interfacial region was not influenced by ML baseplate position. (Fig. 3b).

4.2 Lateral periprosthetic region

Stress in the lateral region increased significantly when the load was predominantly lateral, and decreased when the load was progressively shared with the medial side (Fig. 4a). This finding was dependent on implant position, with a greater decrease in stress in the lateral region when the tibial component was shifted medially. Shifting the baseplate medially away from the lateral cortex caused reduced stress on the lateral region, especially in conditions of important load sharing towards the medial side (Fig. 4b).

4.3 Medial periprosthetic region

Stress in the medial region increased significantly when the load was predominantly medial, and decreased when the load was progressively shared laterally (Fig. 5a). This finding was again dependent on implant position, with a greater decrease in stress on the medial region when the tibial component was shifted laterally. Shifting the baseplate laterally away from the medial cortex caused reduced stress on the medial region, especially in conditions of important load sharing towards the lateral side (Fig. 5b).

5. DISCUSSION AND CONCLUSION

This paper presented a finite element model of a tibia implanted with a tibial knee arthroplasty baseplate in order to investigate the influence of tibial component position and load sharing on the stress distribution in the proximal tibial metaphysis. The average VonMises stress was evaluated in three regions: the tibial component-bone interface, the medial periprosthetic region, and the lateral periprosthetic region of the proximal tibial metaphysis. Knowledge of the stress (and strain) distribution in the tibia after prosthesis implantation and how it changes according to prosthesis positioning and alignment of the limb (medio-lateral load sharing) might be used to predict bone response close to the implant and possibly explain local bone resorption.

The finite element data shows the fact that stress relief can easily occur on the medial side when the tibial implant is not positioned on the medial cortex, and that this could lead to unloading of the medial cortex and to bone resorption. The clinical aspect will be a subject of further investigations. Also the influence of other parameters (i.e. thickness of the tibial baseplate, symmetric geometry of the tibial tray) will be further examined.

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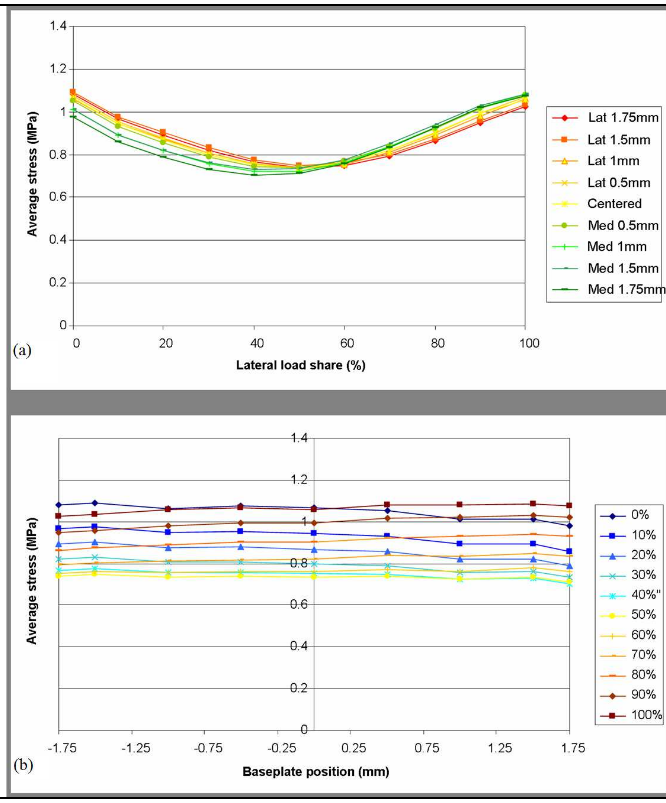

Fig. 4 Average VonMises stress in the interfacial region vs load share (a) and baseplate position (b). 0% lateral share means that the entire load is applied on the medial area. Negative baseplate position means a shift of the component to lateral.

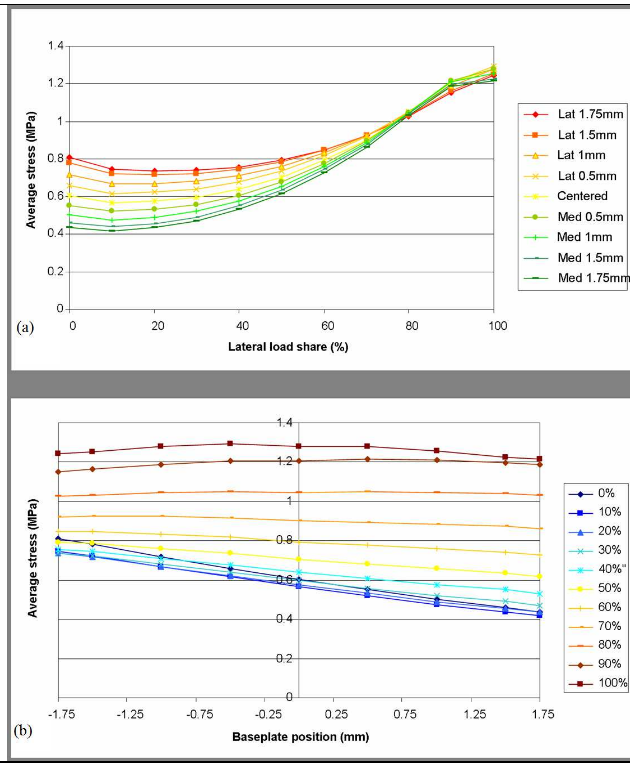

Fig. 5: Average VonMises stress in the lateral region vs load share (a) and positioning (b).

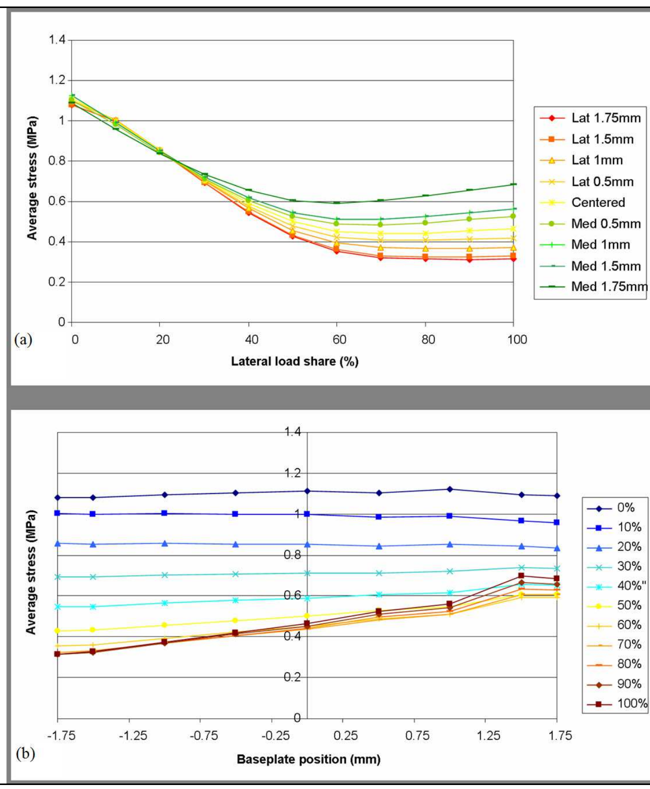

Fig. 6: Average VonMises stress in the medial region vs load share (a) and positioning (b).